Measuring free-living energy expenditure and physical activity with triaxial accelerometry

Measuring Free-Living Energy Expenditure and Physical Activity with Triaxial Accelerometry

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Abstract

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Objective: To investigate the ability of a newly developed triaxial accelerometer to predict total energy expenditure (EE) (TEE) and activity-related EE (AEE) in free-living conditions.

Research Methods and Procedures: Subjects were 29 healthy subjects between the ages of 18 and 40. The Triaxial Accelerometer for Movement Registration (Tracmor) was worn for 15 consecutive days. Tracmor output was defined as activity counts per day (ACD) for the sum of all three axes or each axis separately (ACD-X, ACD-Y, ACD-Z). TEE was measured with the doubly labeled water technique. Sleeping metabolic rate (SMR) was measured during an overnight stay in a respiration chamber. The physical activity level was calculated as TEE $\times$ SMR^{-1}, and AEE was calculated as [(0.9 $\times$ TEE) $-$ SMR]. Body composition was calculated from body weight, body volume, and total body water using Siri's three-compartment model.

Results: Age, height, body mass, and ACD explained 83% of the variation in TEE [standard error of estimate (SEE) = 1.00 MJ/d] and 81% of the variation in AEE (SEE = 0.70 MJ/d). The partial correlations for ACD were 0.73 ($p < 0.001$) and 0.79 ($p < 0.001$) with TEE and AEE, respectively. When data on SMR or body composition were used with ACD, the explained variation in TEE was 90% (SEE = 0.74 and 0.77 MJ/d, respectively). The increase in the explained variation using three axes instead of one axis (vertical) was 5% ($p < 0.05$).

Discussion: The correlations between Tracmor output and EE measures are the highest reported so far. To measure daily life activities, the use of triaxial accelerometry seems beneficial to uniaxial.

Key words: doubly labeled water, sleeping metabolic rate, body composition, activity counts, uniaxial vs. triaxial

Introduction

Being sufficiently physically active is of major importance in the prevention and/or treatment of many diseases in affluent societies. Physical inactivity has been associated with health problems such as cardiovascular disease (1,2), type 2 diabetes (3–6), osteoporosis (7,8), and obesity (9–11). A problem in health-related research is the difficulty in accurately defining physical activity (PA).[1] Methods to assess free-living PA include direct observation, questionnaires, diaries, heart rate monitoring, pedometry, accelerometry, and the doubly labeled water (DLW) method. To this point, DLW is the only technique available to accurately measure total energy expenditure (EE) (TEE) over prolonged periods in daily life. When this technique is combined with a measure of basal metabolic rate, activity-related EE (AEE) or the physical activity level (PAL) can be calculated. The disadvantage is that this technique is expensive and that it does not provide any information about the frequency, intensity, duration, or type of physical activities.

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[1] Nonstandard abbreviations: PA, physical activity; DLW, doubly labeled water; EE, energy expenditure; TEE, total EE; AEE, activity-related EE; PAL, physical activity level; BM, body mass; CSA, Computer Science and Applications Inc.; Tracmor, Triaxial Accelerometer for Movement Registration; SMR, sleeping metabolic rate; SEE, standard error of estimate; FFM, fat free mass; FM, fat mass; RMR, resting metabolic rate.

Accelerometers seem the most promising tools to overcome these problems. Body-fixed accelerometers provide a measure of the total amount, as well as the duration, frequency, and intensity of PA (12). By validating an accelerometer against DLW-derived EE, prediction formulas can be developed to predict AEE, TEE, or PAL from accelerometer counts and other physical characteristics, such as age, sex, height, and body mass (BM). Correlations between accelerometer output and DLW-derived EE measures, such as AEE or TEE, are often very poor and determined mainly by a subject's physical characteristics (13–15). Significant correlations between activity counts and PAL, TEE, and AEE were found for the Computer Science and Applications Inc. (CSA; Shalimar, FL, which is currently known as Manufacturing Technology Inc., Fort Walton Beach, FL) accelerometer (16,17) and the various models of the Triaxial Accelerometer for Movement Registration (Tracmor; Philips Research, Eindhoven, The Netherlands) (18–22). To our knowledge, the highest correlation between PAL and activity counts reported so far was in children, with $R = 0.79$ (20).

Uniaxial accelerometers measure accelerations in one plane (usually vertical), whereas triaxial accelerometers measure accelerations in the anterior-posterior, mediolateral, and vertical direction. Although uniaxial accelerometers are accurate to predict EE during walking, triaxial accelerometers are more suitable when a variety of different activities is involved (12). This has been tested under laboratory conditions by using three different uniaxial accelerometers (23) and one triaxial (12) but, to our knowledge, never in daily life.

Because EE is also dependent on BM and body composition, EE cannot be predicted from accelerometer counts alone. Very often, AEE is divided by BM, but that is correct only when the intercept of the regression line of AEE on BM is zero. At this point, there is still no consensus on how to correct TEE or AEE for body size (24,25).

The purpose of this study was 3-fold: to test the ability of the Tracmor to assess free-living physical activity, to investigate the additional effect of a triaxial over a uniaxial accelerometer to measure the wide variety of daily life activities, and to test which EE parameter correlates best with accelerometer counts.

Research Methods and Procedures

Subjects

Subjects were 30 healthy adults (10 men and 20 women), consisting of six monozygotic twin pairs, eight dizygotic same-sex twin pairs, and one same-sex sibling pair. Subjects were part of a study investigating genetic variation in physical activity. Detailed information about the objective and the protocol of the study was provided. Written informed consent was obtained, and the study was approved by the Ethics Committee of Maastricht University. One subject had to be excluded from all analyses because of loss of the accelerometer. Subjects' characteristics ($n = 29$) are described in Table 1.

Table 1. Subjects' characteristics

	Mean ± SD
n (men/women)	29 (10/19)
Age (years)	24 ± 6
Body mass (kg)	66.8 ± 11.8
Height (m)	1.71 ± 0.10
BMI (kg/m^2)	22.9 ± 4.3
FM (kg)	17.3 ± 9.1
FFM (kg)	49.5 ± 9.2
TEE (MJ/d)	11.5 ± 2.3
SMR (MJ/d)	6.3 ± 0.7
AEE (MJ/d)	4.1 ± 1.5
PAL	1.82 ± 0.21
ACD (kcounts/d)	385 ± 112

Body Composition

Anthropometric measurements were taken in the morning after an overnight stay in a respiration chamber. BM was measured on an electronic scale (ID1 Plus; Mettler Toledo, Giessen, Germany) to the nearest 0.01 kg. Height was measured to the nearest 0.1 cm (Mod.220; SECA, Hamburg, Germany). Body volume was measured with underwater weighing. Residual lung volume was simultaneously measured using the helium dilution technique. Total body water was measured with deuterium dilution according to the Maastricht protocol (26).

Body composition was calculated from body weight, body volume, and total body water using Siri's three-compartment model (27).

Sleeping Metabolic Rate (SMR)

SMR was measured during the second night of a 36-hour stay in a respiration chamber. The chamber measured 14 m^3 and was equipped with a bed, table, chair, freeze toilet (model T 1970, temperature −18°C; T.C.P.S. nv Labo Equipment, Werchter, Belgium), washing bowl, radio, television, and computer (28). EE was calculated from O_2 consumption and CO_2 production according to Weir's formula (29). SMR was defined as the lowest observed EE for 3 consecutive hours during the night, generally between 3 and 6 AM. Room temperature was held constant at 20 ± 1°C.

TEE

TEE was measured with DLW according to the Maastricht protocol (26). In short, after the collection of a baseline urine sample (Day 0), subjects drank a weighed amount of $^2H_2{}^{18}O$ resulting in an initial excess body water enrichment of 150 ppm for deuterium and 300 ppm for oxygen-18. Subsequent urine samples were collected from the second voiding in the morning and a subsequent voiding in the evening on Days 1, 8, and 15. AEE was calculated as (0.9 × TEE) − SMR, assuming diet-induced thermogenesis to be 10% of TEE (25). The PAL was calculated as TEE× SMR^{-1}.

Accelerometry

The Tracmor (Philips Research) is an improved version of the earlier validated Tracmor (21). The Tracmor contains three uniaxial piezo-electric accelerometers, measures 7.2 × 2.6 × 0.7 cm, and weighs 22 grams (battery included). Accelerometer output (counts) represents the rectified and integrated acceleration signal, stored minute by minute for each axis, X (mediolateral), Y (longitudinal or vertical), and Z (anteroposterior) separately. It is attached to the lower back by means of an elastic belt, measuring accelerations in the anteroposterior, mediolateral, and longitudinal axis of the trunk. Subjects were instructed to wear the Tracmor for 15 consecutive days, during waking hours, except during water activities. The Tracmor was designed to enable data storage for at least 3 weeks and to provide optimal wearing comfort in order not to interfere with daily activities. Tracmor output was defined as ACD (ACD for the sum of all three axes or ACD-X, ACD-Y, and ACD-Z for each axis separately), which is the sum of all counts over 15 days divided by 15.

Statistics

Linear multiple regression analysis was used to determine the best predictors of TEE and AEE. Single linear regression was used to test the correlation between PAL and ACD and AEE per kilogram and ACD. To determine the additional effect of triaxial over uniaxial accelerometry, a model was developed with only the counts of the vertical axis (ACD-Y), and the increase in R^2 by adding the other two axes (ACD-X and ACD-Z) was tested for significance. Univariate ANOVA was used to test whether the residuals of the prediction equations were related within twin pairs. The residuals of each model were entered as the dependent variable, and pair was entered as a fixed factor. All analyses were done with SPSS 10.0 for Macintosh (SPSS Inc., Chicago, IL). The statistical significance level was set at $p < 0.05$.

Results

Determinants of TEE

Three different models were used to correct TEE for differences in body size: the first model with SMR, the second with basic characteristics (age, height, sex, weight) (Figure 1), and the third with data on body composition. For each model, ACD significantly contributed to the explained variation in TEE.

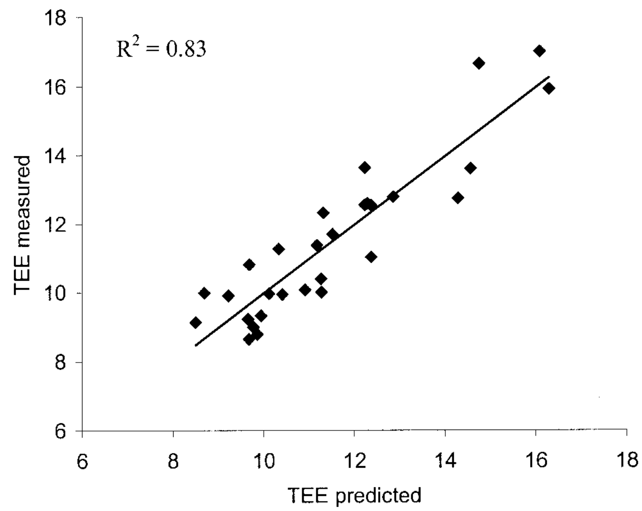

Figure 1: Regression plot of measured TEE vs. predicted TEE. TEE was predicted from age, BM, height, and ACD (regression coefficients presented in Table 2).

With SMR and ACD as the independent variables, the total explained variation of the model was 90% ($R = 0.95$), with a standard error of estimate (SEE) of 0.74 MJ/d or 6.4% of the mean TEE. When a subject's basic characteristics were used, age, height, BM, and ACD significantly contributed to TEE, whereas gender was not significant. Age, height, and BM explained 64% of the variation in TEE, and the Tracmor added 19%, resulting in a total R^2 of 0.83 with an SEE of 1.00 MJ/d or 8.7% of mean TEE. When data on body composition were added, ACD, age, and both fat free mass (FFM) and fat mass (FM) significantly contributed. The total explained variation was 90% ($R = 0.95$), and the SEE was 0.77 MJ/d or 6.7%. Coefficients with standard error, significance levels, and partial correlations of all models are summarized in Table 2.

Determinants of AEE

When AEE was used as the dependent variable, the same independent variables significantly contributed to AEE. For the first model, age, height, and BM explained 48% of the variation in AEE, and ACD increased the R^2 by 33%, resulting in a total R^2 of 0.81 ($R = 0.90$, SEE = 0.70 MJ/d or 17.2% of the mean AEE) (Figure 2). For the second model, data on body composition were used. Age, FFM, FM, and ACD explained 86% of the variation in AEE, with an SEE of 0.59 MJ/d or 14.5%. Results for AEE are summarized in Table 3.

PAL and AEE per Kilogram

Because both PAL and AEE/kg are commonly used measures to express physical activity, simple linear regression

Table 2. Multiple regression analysis with TEE as the dependent variable

Independent	Coefficients	SE	p	Partial correlations
Constant	−7.98	1.28		
SMR (MJ/d)	2.58	0.20	<0.001	0.93
ACD (kcounts/d)	8.57×10^{-3}	1.24×10^{-3}	<0.001	0.80
Model		SEE 0.74	<0.001	$R = 0.95$ ($R^2 = 0.90$)
Constant	−11.18	3.57		
Age (years)	−0.11	0.04	0.007	−0.52
BM (kg)	0.13	0.02	<0.001	0.81
Height (m)	7.69	2.06	0.001	0.61
ACD (kcounts/d)	9.35×10^{-3}	1.77×10^{-3}	<0.001	0.73
Model		SEE 1.00	<0.001	$R = 0.91$ ($R^2 = 0.83$)
Constant	−0.63	1.10		
Age (years)	-8.47×10^{-2}	0.03	0.005	−0.53
FFM (kg)	0.21	0.02	<0.001	0.93
FM (kg)	6.89×10^{-2}	0.02	0.001	0.61
ACD (kcounts/d)	6.47×10^{-3}	1.39×10^{-3}	<0.001	0.69
Model		SEE 0.77	<0.001	$R = 0.95$ ($R^2 = 0.90$)

models are presented for these variables. ACD predicted PAL for 59% ($R = 0.77$; $p < 0.001$), with an SEE of 0.14 or 7.6%. With AEE per kilogram as the dependent variable, the explained variation was 60% ($R = 0.78$; $p < 0.001$), and the SEE was 0.012 MJ/kg per day or 19.3%.

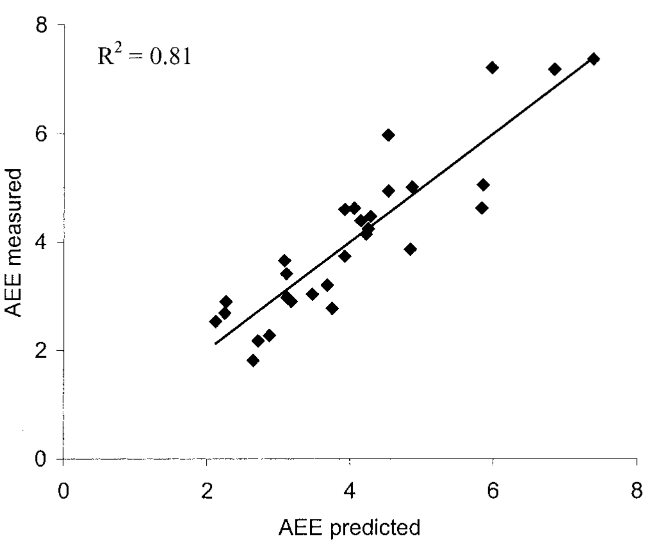

Figure 2: Regression plot of measured AEE vs. predicted AEE. AEE was predicted from age, BM, height, and ACD (regression coefficients presented in Table 3).

Uniaxial vs. Triaxial Accelerometry

To test the additional effect of triaxial accelerometry over uniaxial, we used the models with TEE and AEE as the dependent and subject basic characteristics as the independent variables. Age, height, and BM alone explained 64% and 48% of the variation in TEE and AEE, respectively. When ACD-Y was added, R^2 significantly increased to 0.80 ($p < 0.001$) for TEE and 0.77 ($p < 0.001$) for AEE. Adding the other two axes (ACD-X and ACD-Z) resulted in a significant increase in R^2 from 0.80 to 0.85 ($p = 0.04$) for TEE and from 0.77 to 0.83 ($p = 0.03$) for AEE.

Effect of Twins

To test whether our correlations were influenced by the fact that the subjects were related, we tested for each model whether the residuals were related within pairs. None of the models tested showed a significant pair effect (data not shown).

Discussion

The aim of this study was to test the ability of a new triaxial accelerometer (Tracmor) to measure free-living EE. Sixty-four percent of the variation in TEE could be explained by subject's basic characteristics (age, BM, height), and the Tracmor added 19%, resulting in a total R^2 of 0.83 with an SEE of 8.7%, meaning that individual TEE could be measured to within 1 MJ/d.

Of all of the accelerometers available, only a few have been tested against DLW to provide an estimate of free-

Table 3. Multiple regression analysis with AEE as the dependent variable

Independent	Coefficients	SE	p	Partial correlations
Constant	−8.11	2.50		
Age (years)	-6.65×10^{-2}	0.03	0.013	−0.48
BM (kg)	7.14×10^{-2}	0.01	<0.001	0.75
Height (m)	3.46	1.44	0.025	0.44
ACD (kcounts/d)	7.92×10^{-3}	1.24×10^{-3}	<0.001	0.79
Model		SEE 0.70	<0.001	$R = 0.90$ ($R^2 = 0.81$)
Constant	−3.47	0.85		
Age (years)	-5.52×10^{-2}	0.02	0.016	−0.47
FFM (kg)	0.11	0.01	<0.001	0.87
FM (kg)	4.13×10^{-2}	0.01	0.007	0.51
ACD (kcounts/d)	6.48×10^{-3}	1.08×10^{-3}	<0.001	0.78
Model		SEE 0.59	<0.001	$R = 0.93$ ($R^2 = 0.86$)

living physical activity. Those that were validated often showed poor correlations with DLW-derived EE measures, such as AEE or TEE, or the correlations were determined mainly by a subject's physical characteristics (15). Leenders et al. (13) found that the CSA uniaxial and the Tritrac-R3 days triaxial accelerometer underestimated free-living AEE 59% and 35%, respectively, but only 13 subjects were included in this study. In a study with 136 women (17), the CSA explained an additional 5% of the variation in TEE and AEE after correction for BM. Ekelund et al. (16) tested the CSA in 26 children and found an R^2 of 0.34 between CSA and PAL and a partial correlation of 0.66 with AEE after adjusting for BM. The CSA seems to be the only commercially available accelerometer that correlates reasonably with DLW-derived activity measures. The Tracmor is not commercially available yet, but so far, of all of the accelerometers tested, the Tracmor seems to correlate best with DLW-derived EE measures, with R^2 values between PAL and activity counts of 0.53 in healthy young adults (18), 0.61 in the elderly (19) and 0.62 in children (20), and between TEE, corrected for basal metabolic rate, and activity counts of 0.90 (21). The current Tracmor is slightly smaller and lighter then the previous version. To our knowledge, the total explained variation in TEE (83%) based only on subjects' characteristics (age, BM, height) and Tracmor counts, is the highest reported so far. Moreover, the Tracmor alone increased the R^2 by 19% (from 0.64 to 0.83) for TEE and by 33% (from 0.48 to 0.81) for AEE. The R^2 of 0.59 between ACD and PAL is comparable with those mentioned above.

In the general population, PAL [TEE × resting metabolic rate $(RMR)^{-1}$] ranges between 1.2 and 2.5 (30), meaning that, ideally, the intercept of the regression line of PAL vs. ACD should be close to 1.2. In our sample, the intercept was 1.27, which is very close to the PAL value of 1.2 for an inactive person. The slightly higher value can be attributed to the fact that we used SMR instead of RMR.

In the regression analysis of PAL vs. counts, there was one outlier with high activity counts for a relatively low PAL. Without this subject, the explained variation increased from 59% to 70%. Although the high activity counts for a low PAL in this subject could be due to bad accelerometer functioning, it might also be related to the approach of correcting TEE for SMR by simply using the ratio. The issue of how to correct TEE for body size or RMR has recently gained new interest (17,25,31). Theoretically, TEE should be divided by RMR or SMR only when the regression of TEE on SMR has a zero intercept. Because the impact of a non-zero intercept, as was the case in our sample, is always bigger at the lower range of EE, it is, perhaps, no coincidence that the outlier was the subject with the lowest SMR. When TEE was corrected (TEE_{adj}) for SMR by adding the residual of the regression of TEE on SMR to the mean TEE, the R^2 between TEE_{adj} and ACD was 0.64 instead of 0.59 with PAL.

The same problem occurs when trying to correct AEE for BM or body composition. Many authors use AEE × BM^{-1} as a measure of physical activity. Prentice et al. (24) suggested using BM to the exponent of 0.5 rather than 1 as the denominator because not all activities have the same weight-bearing impact on AEE. However, they also emphasized that it is not recommended to use this as a universal approach and that there is probably no generally applicable adjustment factor. According to our data, dividing AEE by BM would be an oversimplification because not only BM but also height and age significantly contributed to the explained variation in AEE. Furthermore, when data on body composition are available, a distinction should be made between FFM and FM given their different impact on AEE. FFM is directly related to AEE because it is the metabolic component of BM, whereas FM is related to AEE due to its weight-bearing effect. As shown in Table 3, both FFM and FM contributed to the explained variation in AEE to a different extent. In agreement with Prentice et al. (24), the relative contribution of FFM and FM to AEE would be dependent on the activity performed. Therefore, dividing AEE by FFM only would again result in an oversimplification.

Many accelerometers are uniaxial, measuring accelerations only in the vertical plane. Ayen et al. (23) simulated the additional effect of triaxial over uniaxial accelerometry by using three uniaxial accelerometers mounted in three different directions at the waist. They concluded that the output of three accelerometers correlated better with AEE than the output of any of the uniaxials separately. Bouten et al. (12) were the first to test the contribution of different directions to the estimation of AEE using a single triaxial accelerometer. The results were in agreement with Ayen et al. (23) that for a variety of activities, triaxial assessment is better than uniaxial. Leenders et al. (12) simultaneously validated the Tritrac triaxial and the CSA uniaxial accelerometer against DLW in 13 healthy women. The explained variation in AEE was 29% ($R = 0.54$, not significant) and 20% ($R = 0.45$, not significant) for the Tritrac and the CSA, respectively. However, because two devices from different manufacturers were used, no conclusions can be drawn regarding the possible benefits of triaxial vs. uniaxial accelerometry. To our knowledge, this is the first study comparing triaxial with uniaxial accelerometry using a single device, under daily life conditions, by comparison with DLW. After correcting for BM, height, and age, the vertical axis (ACD-Y) explained an additional 16% of the variation in TEE. Adding the other two axes caused a significant increase in R^2 with another 5%, resulting in a total explained variation of 85%. In comparison, when the sum of all three axes was used, the explained variation in TEE was 83%. Therefore, to measure the wide variety of daily life activities, triaxial accelerometers are more suitable than uniaxial.

We are aware that the current study population was somewhat unusual because it consisted of twins. Statistically, there was no significant twin effect on the residuals of any of the variables tested. Therefore, we believe that the reported correlations are not influenced by the fact that our subjects were related, although the reported SEE might be somewhat lower than in a more diverse study population.

A problem inherent to DLW studies is the low number of subjects. Therefore, no attempt was made to split the group, using one-half to generate the equation and the other one-half to validate it. Larger study samples would allow more accurate prediction equations, with less susceptibility to outliers. The advantage is that we included an accurate measure of SMR and body composition to study the impact of the different variables on EE.

In conclusion, TEE can be explained for 90% (SEE = 6% to 7%) when data on either SMR or body composition and Tracmor output are included and for 83% based on subjects' characteristics and Tracmor only (SEE = 8.7%); using triaxial accelerometers instead of uniaxial results in an increase of R^2 up to 5%; and because there is no general applicable coefficient to adjust TEE or AEE for body size and composition, the use of regression analysis is preferred over the use of simple ratios.

Acknowledgments

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References

1. **Fang J, Wylie-Rosett J, Cohen HW, Kaplan RC, Alderman MH.** Exercise, body mass index, caloric intake, and cardiovascular mortality. *Am J Prev Med*. 2003;25:283–9.
2. **Panagiotakos DB, Chrysohoou C, Pitsavos C, et al.** Risk factors of stroke mortality: a 40-year follow-up of the Corfu cohort from the Seven-Countries Study. *Neuroepidemiology*. 2003;22:332–8.
3. **Hu FB, Li TY, Colditz GA, Willett WC, Manson JE.** Television watching and other sedentary behaviors in relation to risk of obesity and type 2 diabetes mellitus in women. *Jama*. 2003;289:1785–91.
4. **Hu G, Qiao Q, Silventoinen K, et al.** Occupational, commuting, and leisure-time physical activity in relation to risk for Type 2 diabetes in middle-aged Finnish men and women. *Diabetologia*. 2003;46:322–9.
5. **Kriska AM, Saremi A, Hanson RL, et al.** Physical activity, obesity, and the incidence of type 2 diabetes in a high-risk population. *Am J Epidemiol*. 2003;158:669–75.
6. **Mensink M, Feskens EJ, Saris WH, De Bruin TW, Blaak EE.** Study on Lifestyle Intervention and Impaired Glucose Tolerance Maastricht (SLIM): preliminary results after one year. *Int J Obes Relat Metab Disord*. 2003;27:377–84.
7. **Neville CE, Murray LJ, Boreham CA, et al.** Relationship between physical activity and bone mineral status in young adults: the Northern Ireland Young Hearts Project. *Bone*. 2002;30:792–8.
8. **Kai MC, Anderson M, Lau EM.** Exercise interventions: defusing the world's osteoporosis time bomb. *Bull World Health Organ*. 2003;81:827–30.
9. **Weinsier RL, Hunter GR, Desmond RA, Byrne NM, Zuckerman PA, Darnell BE.** Free-living activity energy expenditure in women successful and unsuccessful at maintaining a normal body weight. *Am J Clin Nutr*. 2002;75:499–504.
10. **Williams PT.** Vigorous exercise and the population distribution of body weight. *Int J Obes Relat Metab Disord*. 2004;28:120–8.

11. **Jebb SA, Moore MS.** Contribution of a sedentary lifestyle and inactivity to the etiology of overweight and obesity: current evidence and research issues. *Med Sci Sports Exerc*. 1999;31(Suppl 11):S534–41.
12. **Bouten CV, Westerterp KR, Verduin M, Janssen JD.** Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Med Sci Sports Exerc*. 1994;26:1516–23.
13. **Leenders NY, Sherman WM, Nagaraja HN, Kien CL.** Evaluation of methods to assess physical activity in free-living conditions. *Med Sci Sports Exerc*. 2001;33:1233–40.
14. **Rafamantanantsoa HH, Ebine N, Yoshioka M, et al.** Validation of three alternative methods to measure total energy expenditure against the doubly labeled water method for older Japanese men. *J Nutr Sci Vitaminol (Tokyo)*. 2002;48:517–23.
15. **Johnson RK, Russ J, Goran MI.** Physical activity related energy expenditure in children by doubly labeled water as compared with the Caltrac accelerometer. *Int J Obes*. 1998; 22:1046–52.
16. **Ekelund U, Sjöström M, Yngve A, et al.** Physical activity assessed by activity monitor and doubly labeled water in children. *Med Sci Sports Exerc*. 2001;33:275–81.
17. **Masse LC, Fulton JE, Watson KL, Mahar MT, Meyers MC, Wong WW.** Influence of body composition on physical activity validation studies using doubly labeled water. *J Appl Physiol*. 2004;96:1357–64.
18. **Bouten CV, Verboeket-van de Venne WP, Westerterp KR, Verduin M, Janssen JD.** Daily physical activity assessment: comparison between movement registration and doubly labeled water. *J Appl Physiol*. 1996;81:1019–26.
19. **Meijer EP, Goris AH, Wouters L, Westerterp KR.** Physical inactivity as a determinant of the physical activity level in the elderly. *Int J Obes Relat Metab Disord*. 2001;25:935–9.
20. **Hoos MB, Plasqui G, Gerver WJ, Westerterp KR.** Physical activity level measured by doubly labeled water and accelerometry in children. *Eur J Appl Physiol*. 2003;89:624–6.
21. **Goris AH, Meijer EP, Kester A, Westerterp KR.** Use of a triaxial accelerometer to validate reported food intakes. *Am J Clin Nutr*. 2001;73:549–53.
22. **Westerterp KR, Bouten CVC.** Physical activity assessment: Comparison between movement registration and doubly labeled water method. *ZErnahrungswiss*. 1997;36:263–7.
23. **Ayen TG, Montoye HJ.** Estimation of energy expenditure with a simulated three-dimensional accelerometer. *J Ambulatory Monitoring*. 1988;1:293–301.
24. **Prentice AM, Goldberg GM, Murgatroyd PR, Cole TJ.** Physical activity and obesity: problems in correcting expenditure for body size. *Int J Obes*. 1996;20:688–91.
25. **Westerterp KR.** Energy metabolism and body composition: general principles. *Eur Respir Mon*. 2003;24:1–10.
26. **Westerterp KR, Wouters L, Marken-Lichtenbelt WDv.** The Maastricht protocol for the measurement of body composition and energy expenditure with labeled water. *Obes. Res.* 1995;3(Suppl 1):49–57.
27. **Siri WE.** Body composition from fluid spaces and density: analysis of methods. In: Henschel JBaA, ed. *Techniques for Measuring Body Composition*. Washington, DC: National Academy of Science National Research Council; 1961, pp 223–4.
28. **Schoffelen PF, Westerterp KR, Saris WH, Ten Hoor F.** A dual-respiration chamber system with automated calibration. *J Appl Physiol*. 1997;83:2064–72.
29. **Weir JBdV.** New methods for calculating metabolic rate with special reference to protein metabolism. *J. Physiol.* 1949;109: 1–9.
30. **Westerterp KR.** Alterations in energy balance with exercise. *Am. J. Clin. Nutr.* 1998;68(suppl):970–4S.
31. **Ekelund U, Yngve A, Brage S, Westerterp K, Sjöström M.** Body movement and physical activity energy expenditure in children and adolescents: how to adjust for differences in body size and age. *Am J Clin Nutr*. 2004;79:851–6.